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LONG-TERM GOALS

Teleoperated platforms being introduced into the field are expected to take a larger role in access and neutralization of area denial and explosive devices. The work includes examination, identification, and disposal of ordnance. These systems that consist of a base platform and many degree-of-freedom manipulator with end effector get carried to the work site by vehicles. Current commercial and developmental arms are either too expensive for EOD or do not have the flexibility and strength-to-weight ratio necessary for Render Safe Procedures. Technologies leading to serpentine manipulators incorporating muscle-like electroactive polymer (EAP) actuators are explored. Manipulators using these technologies will provide to the operator, who's out of harm's way, high dexterity or mobility, which makes it valuable for complex and obstructed environments that are often encountered.

OBJECTIVES

The key to development of the manipulator is a new actuation technology, an EAP artificial muscle that has been developed at SRI. Muscle-like actuators based on this technology have the combination of high energy-output-to-weight ratio, large stroke capability, good speed of response, and high efficiency unavailable in other actuation technologies. The use of such actuators will allow for the development of an extremely lightweight and slender manipulator with a sufficient number of degrees of freedom to negotiate around obstacles. The objective is to develop this technology so they can demonstrate that a highly dexterous serpentine manipulator with "follow the leader" control methodology can be realized for EOD access missions. A secondary objective is to demonstrate the application of this technology to legged locomotion of a small UXO-gathering platform.

APPROACH

A breakthrough is needed to reduce the cost for a high strength, high dexterity, and low cost manipulator. A promising technical approach to this problem is the use of EAPs as actuators. Thin snake-like manipulators with a high number of degrees of freedom that would be capable of positioning an end-effector in a highly cluttered environment are not available. The main obstacle to their development has been the lack of lightweight and compact actuators capable of producing the needed forces (or torque), displacements, and speed of response. Many multi-articulated arm designs have placed the actuators on the manipulator base to avoid the issue of actuator size and mass.

The basic building block of SRI's EAP technology is a rubbery polymer that is sandwiched between two compliant electrodes. When a voltage difference between the two electrodes is applied, the resulting electrostatic force compresses the thickness and expands the area of the polymer film. This deformation of the film can be used for actuation.

The energy output of electroactive polymer muscle can be very large. Silicone-rubber, a material that has proven to produce rugged reliable actuators, has produced strains in excess of 100%, pressures greater than 100 psi and specific energy densities exceeding that of all known field actuated materials (such as piezoelectrics and magnetostrictive materials) in response to an applied voltage. These values are much larger than those suggested by the breakdown voltages quoted in industrial literature. The key to achieving higher breakdown voltages is to use high-quality thin films, and eliminate any remaining electrical defects prior to operation. Key technical challenge in this project include scaling up the extremely high performance measured in small samples and developing lightweight actuator designs that efficiently convert the high energy of deformation of the polymer into mechanical work.

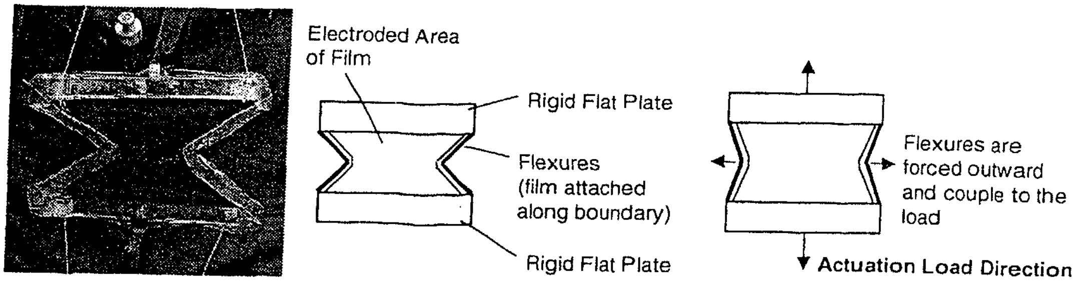
WORK COMPLETED

Work during FY99 focused on improving the performance of the linear actuator elements based on the electroactive polymer materials. These linear actuator elements may serve as muscle-like actuators for a biomorphic serpentine manipulator or legged robot. These elements may also be incorporated into a rotary motor that may be used to drive the joints of a serpentine manipulator. Actuator improvements included aspects of materials and fabrication as well as design.

SRI's most reliable actuators to date have been made from silicone rubber polymers (polydimethyl siloxane). In the past, SRI has had problems reliably producing high quality spin-coated films of silicone needed to make linear actuator elements. This year they identified a commercially available silicone (NuSil Corporation, Carpenteria, California) that reliably produces good-quality films and actuators with good performance. Much of this year's work employed this silicone, NuSil CF19-2186.

In the area of design, much of the effort has been directed at improving specific energy output of the actuator elements. Last year they focused on ways to couple the energy of deformation to output. The "spider" actuator design discussed last year was effective at improving energy coupling. However, this design requires much inactive structure in order to function well. This past year, they invented a novel design, a "bowtie" actuator that requires less inactive structure. Another advantage of the bowtie design is that the actuator elements are flat and can easily be stacked to produce greater forces.

The bowtie consists of two rigid strips at the ends of the actuator. Two mirror imaged, hinged strips run along the remaining edges of the film. Each hinged strip is bent roughly 45 degrees in the plane of the film. When the film is actuated, the expansion of the film in the direction normal to the rigid end strips causes the end strips to move apart. Additionally, the expansion of the film in the direction orthogonal to these strips causes the hinged strips to straighten, and separates the rigid end strips. In this manner, the bowtie couples both directions of film expansion into the load attached to the rigid end strips. Figure SRI1 shows the structure and operation of a bowtie actuator.



a) Bowtie element shown with a 2 g mass. Such elements can weigh less than 1 g.

b) Bowtie structure in relaxed state

c) Bowtie in activated state

Figure SRI1. Structure and operation of a bowtie artificial muscle actuator

There are many parameters that may be varied on the bowtie actuator, such as the aspect ratio of the actuator and the width of the narrow center section. A finite element model with a Mooney-Rivlin constitutive model of the deformation of the polymer material was used to determine that the best results were obtained with actuators that were as wide as practical (high-aspect ratio) with a narrow center. Experiments confirmed this. More recently they have begun experimenting with high-aspect ratio bowties where polymer is pre-strained in the direction orthogonal to direction of actuation. This anisotropic pre-strain makes the film appear stiffer in the direction not coupled to output. Therefore the coupling to output should be more efficient. SRI demonstrated the utility of the new bowtie designs by employing them as muscle-like actuators in a robotic leg and as the driving elements in a rotary motor.

Although silicones gave good performance, SRI continued to identify and evaluate polymer with better performance (particularly, specific energy density). They identified a copolymer of polyvinylidene fluoride and trifluroethylene, P(VDF-TrFE), as promising material based on SRI's own measurements and work by Professor Qiming Zhang at Pennsylvania State University. The Penn State material is irradiated to affect molecular structure and further enhance electrostrictive properties. SRI was able to reproduce the high energy density of this material with samples purchased from Penn State. However, the small samples have defects that have not yet allowed the production of reliable actuator elements.

SRI also evaluated non-irradiated P(VDF-TrFE) obtained directly from the manufacturer (Solvay). Even with non-irradiated material, SRI was obtained very high specific energy output. They were able to use this material to produce bowtie type actuators. A disadvantage of this material is that it exhibits creep. An additional problem is that the electrical to mechanical coupling of the material is lower than that of silicone. This lower coupling may make it difficult to achieve good overall energy efficiency.

SRI acquired a Dynamic Mechanical Analyzer (EnduraTEC, Eden Prairie, Minnesota) for purposes of better determining the viscoelastic behavior of the electroactive polymers. The DMA data confirmed their earlier assumptions that the elastic modulus was relatively constant over the range of frequencies of interest (DC to 100 Hz) and that the loss tangent was small. The amount of energy lost to viscoelastic effects was about 15% in the silicones and 25% in the P(VDF-TrFE) (non-irradiated).

The most common failure mode for an actuator element is electrical breakdown, which usually occur during the initial testing or burn-in. However, breakdowns may also happen after sustained use. It would be good to provide actuators with an ability to self-heal small breakdowns. To this end, they experimented with a variety of new electrode materials. Typically on silicones, electrode material of spray-coated carbon graphite / carbon blacks in silicone binder is used. This material will not self-heal unless the coating is extremely thin, but coatings that are sufficiently thin are too resistive to be good electrodes. Metals, as previously noted, cannot stretch sufficiently to act as electrodes. SRI developed a conductive polymer material based on doped polyanilene that did have the ability to self heal while maintaining good conductivity. This material is dissolved in a petroleum solvent and may be spray-coated. This material works well on P(VDF-TrFE). However, this material gave poor results with silicones. This performance is due to poor adhesion between the electrode material and silicone, as well as the inability of electrode material to survive the extremely large strains that silicones produce.

RESULTS

Using the newer silicone polymers and bowtie designs and fabrication techniques, SRI can reliably produce linear actuator elements with good performance. The performance achieved is better than most alternative actuator technologies, such as piezoelectrics and is suitable for incorporation into small walking robots. The energy density is nearly that of natural muscle (typically 0.01 J/g). These muscle-like actuators were integrated with a robotic leg. To achieve what is needed for a practical robot, they would stack actuators. SRI demonstrated up to five operating in parallel. In principal, there is no limit to how many actuators could be operated in parallel. SRI plans to demonstrate ten in parallel soon.

Table 1. Typical Performance of Bowtie Linear Actuators

	Silicone 2186	P(VDF-TrFE)
Total mass (g)	1.4	3
Active material mass (g)	.4	0.12
Max. Force (N)	1.2	10
Max. Stroke (mm)	4	1.5
Specific Energy (total mass) (J/g)	0.0034	0.005
Specific Energy (active material mass) (J/g)	0.012	0.12
Estimated electromechanical coupling efficiency (%)	20	5

The performance of the bowtie linear actuators, while fine for legged locomotion, isn't yet sufficient to drive a long-thin serpentine manipulator (e.g., diameter less than 10 cm, length greater than a meter). Specific energy output of muscle is a limitation on length. Nonetheless, anticipating material and design improvements, SRI constructed a direct-drive spherical joint based on the bowtie linear actuator. Four high-aspect ratio bowties span two square plates measuring 3.5 cm on a side. Actuation of different combinations of bowties can give motion in any direction. The joint was capable of 6 degrees of tilt from the normal axis, and the bowties were just 2.5 cm high, so the radius of curvature of a manipulator composed of such joints is 15 cm (ignoring joint interference). This suggests that such a joint would allow for good kinematics and dexterity in a meter-long manipulator. To increase force, each bowtie could be replaced by several operated in parallel. SRI estimates that at least 20 N of force is required to operate a meter-long manipulator with mass of 200 g. Actuators for such a manipulator require specific energy density of 0.02 J/g. They have not achieved this energy density, but are close. Improvements in design, fabrication and materials should allow them to reach this soon.

Although the direct drive, spherical joint holds promise, a motor-driven joint with high gear ratio could meet the energy density demands at the expense of speed. An additional advantage of the motor drive is that the device could hold position with no power. In FY'98 they demonstrated a motor that converts the reciprocating motion of a pair of rolled actuator elements into rotary motion by rectifying the oscillations using a one-way clutch. In FY'99 they improved this design to incorporate the better performing bowtie actuator elements in place of the rolls, resulting in greater performance. The no-load output speed with the new design was 600 rpm, compared to 115 rpm with the previous design. SRI also used the new driver setup to drive the spherical joint setup so as to make the free end of the joint orbit (nutate). This test demonstrates their ability to make a nutating motor function.

IMPACT/APPLICATIONS

There is a specialized need for an arm that can move precisely inside an object without toughing any surfaces. Arm control must be precise, slow, and deliberate. The inadvertent bumping of the arm into bomb components, electronics, or structure may have disastrous results. The EOD technician must be able to spatially determine the exact location of the arm during a procedure. The arm must operate at a slow speed. A computer will track where the arm has been and, therefore, where it may not deviate when withdrawn. An artificial muscle, electroactive material construction, would have a vast array of applications that would serve as prime movers for: "sloth" type serpentine arms; inexpensive bomb disablement and UXO retrieval robots; and artificial prostheses.

TRANSITIONS

This technology will transition to both conventional EOD Joint Service programs and specialized mission groups that support the Army's 52nd Ordnance Group. The technology for polymer muscles will be transitioned to ongoing EOD programs to enhance actuator performance and reduce cost.

RELATED PROJECTS

In FY99, SRI began a separate project funded by ONR to develop a small, legged UXO-handling robot using their artificial muscle actuators. This work will build directly on their development of the linear artificial muscle actuators and leg demonstration performed under the current contract.

SRI also has a project with DARPA, now in the second of a three-year effort, to develop a biomorphic, flapping-wing, micro air vehicle. SRI is pursuing using EAP muscles to actuate flapping motion.

Since 1992, SRI has been working under contract with the Micro Machine Center of Japan, funded by the Japanese government, to develop small actuators for small robots and micro machine applications. This work has focused on the development of EAP materials and small actuator devices.

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